15.4 OBSERVATIONS PERTAINING TO THE DEVELOPMENT OF LARGE CLOUD DROPLETS IN WARM CUMULI

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1. INTRODUCTION

This study focuses on the initial development of drizzle through warm processes in shallow cumuli. This topic has been the focus of many field projects and modeling studies, yet numerous questions remain unanswered relating to where and when drizzle drops first form and what processes are relevant to their formation.

This work attempts to address some of these questions by examining the nature of droplet spectra observed in small cumuli. The evolution of the droplet spectra and observations of large cloud droplets are discussed. An attempt is made to better understand how the large droplet "tail" of the spectrum evolves in space and time.

2. DATA SET

The observations presented herein were made during the Small Cumulus Microphysics Study (SCMS) in east-central Florida during summer, 1995. The focal point for the observations was the ground-based CP2 radar operated by NCAR. This radar provided measurements of equivalent reflectivity factor at two wavelengths allowing for separation of the Bragg and Rayleigh scattering components of the reflectivity echo (Knight and Miller, 1998). Clouds chosen for study were within 20 km of the radar to ensure good sensitivity and spatial resolution. Volume scans were completed every 2 to 3 minutes. Radar measurements provide the framework for interpreting the measurements from aircraft in situ probes.

Three cloud penetrating aircraft made measurements of pertinent microphysical parameters such as hydrometeor size distributions, air motion, and thermodynamic variables. Each aircraft (NCAR C130, UW KingAir, Meteo-France Merlin) carried an FSSP-100 and an OAP 1DC. The FSSP's provided cloud droplet size distributions for particles with diameters roughly 2 to 60 µm. The OAP's provided distributions for droplets 10 to 200 µm and larger.

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Data used in this study from the UW KingAir were processed and archived at 10 Hz. For a nominal airspeed of 100 m s^{-1}, this corresponds to 10 m along-path resolution. Data from the other aircraft were provided at 1 Hz, translating into roughly 100 m resolution.

Measurements from the Wyoming Cloud Radar (WCR) were also used in this study (for information about this radar and a list of relevant publications see the web pages at http://www-das.uwyo.edu/wcr/). This radar is mounted on the KingAir and provides measurements of both Rayleigh reflectivity factor and vertical Doppler velocity. The novelty of this radar is its ability to provide high resolution (roughly 15 m along-track, 30 m along-beam) essentially instantaneous vertical cross sections as the KingAir penetrates clouds. Once the Doppler velocities have been corrected for aircraft motion the resultant is, to a good approximation, simply the vertical air speed, since in these clouds the contribution due to droplet terminal velocity is negligible.

3. OBSERVATIONS

Observations made on two days (Aug05 and Aug07) during SCMS are presented in this study. The general atmospheric conditions were quite similar on these days. The lowest 1.5 km was quite moist with a nearly dry adiabatic lapse rate. Above this, at 2 km, a subsidence inversion acted to suppress any deep convection.

Wind speeds from the surface to 3 km were between 3 and 7 m s^{-1}. Wind directions were easterly (from the ocean) on Aug05 and were westerly (from the land) on Aug07. Shear was very weak, roughly 10^{-3} s^{-1}.

Clouds were continually being scanned by CP2. Also, the clouds were being penetrated by aircraft with the C130 at or near cloud base, the KingAir at mid-levels (300 to 1000 m above cloud base), and the Merlin near cloud top. Maximum observed reflectivity factors were less than 0 dBZ_e for clouds on Aug05 and less than -5 dBZ_e for those on Aug07.

3.1 *General Cloud Characteristics*

The observation period lasted approximately 1.5 hours on each day. Detailed measurements were made in 15 clouds. Of those, data from six of the clouds (3 on each day) were comprehensive enough to be included in this analysis.

The typical lifetime of a given cloud was roughly 30 minutes. During its lifetime, each cloud was observed to exhibit pulsating growth (French *et. al.,* 1997). Individual pulses may be tracked as single entity "bubbles" within the WCR data. In general, subsequent pulses achieved greater altitudes and larger reflectivity factors than did earlier pulses.

Cloud bases were at roughly 900 m on both days and tops extended to between 2.5 and 3 km. Maximum observed cloud liquid water contents (CLWC) were between 1.5 and 2.0 g m^{-3} at mid-levels and above. Maximum observed vertical velocities were about 5 m s^{-1} on Aug05 and 8.5 m s^{-1} on Aug07. Cloud droplet concentrations as large as 800 cm^{-3} were observed on Aug07, while on Aug05 concentrations were significantly less, roughly 300 cm^{-3}.

There is, in general, a strong positive correlation between CLWC and vertical velocity and between droplet concentration and vertical velocity. In each case the correlation decreases with increasing height above cloud base. Maximum droplet concentrations remain fairly constant with height, although the percentage of the total cloud penetration of such areas does decrease with increasing altitude.

3.2 *Cloud Droplet Distributions*

Droplet size distributions are on average bi-modal, with one peak between 2 and 8 µm and a second peak occurring with diameters between 18 and 40 µm (Figure 1). Both modes are detectable in the lowest half of the clouds, but the smallest mode becomes increasingly difficult to detect with increasing altitude.

One feature common to all of the spectra is a sharp decrease in the concentration at sizes a few microns larger than the diameter of the larger mode. From this, we define the roll-off diameter as the smallest size at which the droplet concentration decreases by at least one order of magnitude over a range of 5 µm in diameter. The roll-off diameter is useful as the separation between the high concentration cloud droplets grown principally through condensation and the low concentration large droplets[1] grown through coalescence.

Figure 2 illustrates the relationship between the roll-off diameter and altitude. As height above cloud base increases, so does the rolloff diameter.

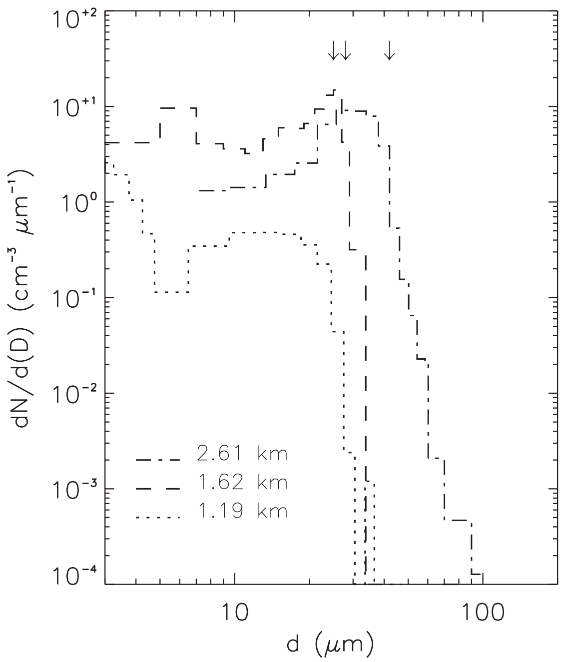

Figure 1: Droplet size distributions averaged over penetrations at three levels for the same cloud on Aug05. Data from 1.19 km (dotted) is from the C130, 1.62 km (dashed) from the KingAir, and 2.61 km (dashed-dotted) from the Merlin. The arrows at the top indicate the calculated roll-off diameter for each of the three spectra.

This is interpreted as evidence for condensational growth of the cloud droplets as they ascend. An interesting aspect of the roll-off diameter is that for any given level and day it remains constant. The roll-off diameter appears independent of the growth stage the cloud. Also, there is no significant cloud to cloud variation on a given day.

The data do indicate that the roll-off diameter varies with the total maximum droplet concentration. On Aug07, droplet concentrations are 2.5 times larger than those observed on Aug05 and the corresponding roll-off diameter is 6 to 10 µm smaller for any given altitude (see Figure 2).

3.3 *Observations of Large Droplets*

The concentration of large droplets is significantly less than the concentration of the smaller cloud droplets, generally by 5 to 6 orders of magnitude. Also, the distribution of the larger

[1] Droplets larger than the roll-off diameter will be hereafter referred to as large droplets while those smaller will be referred to simply as cloud droplets.

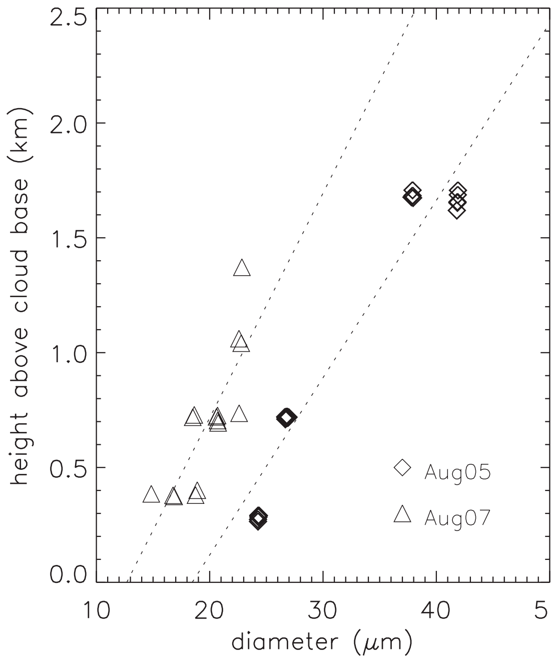

Figure 2: Roll-off diameter as a function of altitude calculated from droplet spectra in six clouds on two days. Measurements from all three aircraft in three clouds are included in the Aug05 data. The Aug07 data are all from the KingAir, with penetrations made in three clouds. The dotted lines represent least squares line fits for each of the two days.

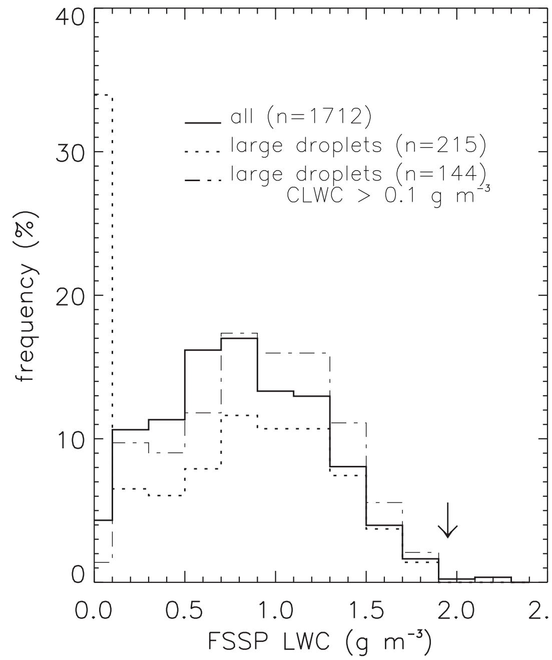

Figure 3: Distributions of cloud liquid water content from 13 penetrations of three clouds on Aug05. All of the penetrations were made at 700 m above cloud base. There are a total of 1712 points (solid) of which, 215 correspond to instances when at least one droplet was detected by the 1DC probe (dotted). There are 144 points (dashed-dotted) when large droplets were detected in the presence of CLWC's greater than 0.1 g m^{-3}. The adiabatic CLWC was roughly 1.95 g m^{-3} and is indicated by an arrow. This data is from the KingAir and was processed at 10 Hz.

droplets flattens out, defining the "tail" as it is often referred to in the literature.

Most of the data presented in this section are taken from the UW KingAir, mainly because the availability of this data at high rate. The clouds were usually less than 1 km across, often providing only 5 to 8 data points for those data available at 1 Hz.

Larger droplets were never detected less than 250 m above cloud base. Near cloud top concentrations were great enough to calculate reasonable size distributions at 1 Hz. At mid-levels, droplets were often detected but concentrations were so low that it was necessary to calculate the average over an entire penetration to determine reasonable values.

An indication of where these droplets were located can be obtained by investigating the conditions at the locations at which these droplet were observed. Figure 3 shows histograms of CLWC constructed from all of the penetrations made in the three clouds on Aug05. The solid line in Figure 3 is the distribution of CLWC for all Points while the dotted line is the distribution for those locations at which large droplets were detected by the OAP. Both are taken from KingAir data archived at 10 Hz.

The majority of points at mid-levels have CLWC's between 0.5 and 1.3 g m^{-3}. The number of points with higher CLWC decreases nearly linearly up to adiabatic values (roughly 1.95 g m^{-3}). The regions of high CLWC are generally located near the center of the cloud collocated with the strongest upward vertical velocities. It is apparent that these areas are regions of relatively unmixed adiabatic ascent.

At mid-levels, large cloud droplets are detected in only 12% of the total observations. Thirty-five percent of these droplets are in regions with CLWC's less than 0.1 g m^{-3}. Vertical velocities in these regions are weak and generally downward so it is reasonable to assume that these droplets are being carried down from above.

Only 8% of the cloud regions with CLWC's greater than 0.1 g m^{-3} contain large droplets.

There is a slight tendency for the large droplets to be in regions of greater CLWC and stronger updrafts. The droplets in these regions will be ascending with the parcels and growing through coalescence.

4. REFLECTIVITY CALCULATIONS

Reliable interpretation of radar reflectivity depends on what size particles are dominating the measured reflectivity. Assuming Rayleigh scattering, the reflectivity factor depends the sixth moment of the size distribution of scatterers. Thus, it is generally assumed that the largest particles within a distribution dominate the reflectivity. This need not always be the case, especially for distributions that have a very steep slope and significantly lesser concentrations of larger droplets.

Calculations of Rayleigh reflectivity factor based on data from the FSSP's and OAP's indicate that the reflectivity factor due to droplets smaller than the roll-off diameter remains relatively constant through a cloud's evolution. Reflectivity factors due to cloud droplets are roughly -17 to -15 dBZ at mid-levels and -9 dBZ near cloud top for clouds on Aug05 and 3 to 4 dB less for clouds on Aug07. On both days, calculated reflectivity factors due to larger droplets increase throughout the lifetime of the cloud and eventually exceed those due to cloud droplets. The time at which this transition takes place is not well correlated with any of the measured parameters.

5. DISCUSSION

No large droplets were detected within 250 m of cloud base for any of the clouds on these two days. Between 300 and 800 m above cloud base, large droplets were detected but the concentration of these droplets was very low. Large droplets detected in regions of low CLWC and weak downdrafts appear to have been transported from higher altitudes. A simple calculation of condensational growth reveals a droplet 100 µm in diameter in similar conditions would evaporate in roughly 200 seconds, possibly explaining why no large droplets were detected near cloud base. Large droplets detected within adiabatic cores must be either newly formed droplets from coalescence nuclei or have been mixed in from other regions of the cloud. It is not clear which mechanism is responsible for the these large droplets.

Near cloud top, specifically on Aug05, concentrations of large cloud droplets are roughly one order of magnitude larger than at mid-levels. Also at this altitude, the roll-off diameter is greater than 40 µm. Calculations based on a continuous collection model reveal the largest cloud droplets would grow through coalescence and achieve diameters of 100 µm in less than five minutes (Rogers and Yau, 1989).

Calculations based on probe data indicate there is a transition between reflectivity being dominated by cloud droplets and reflectivity being dominated by large droplets. The reflectivity due to cloud droplets remains relatively constant through a cloud's lifetime. As expected, this is consistent with the roll-off diameter since it is the largest cloud droplets that have the more significant contribution to the reflectivity factor. As the cloud evolves, large droplets become numerous enough that they begin to dominate the Rayleigh echo. The transition time varies greatly from cloud to cloud, yet knowledge of where and when this occurs is required for interpretation of the radar data.

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